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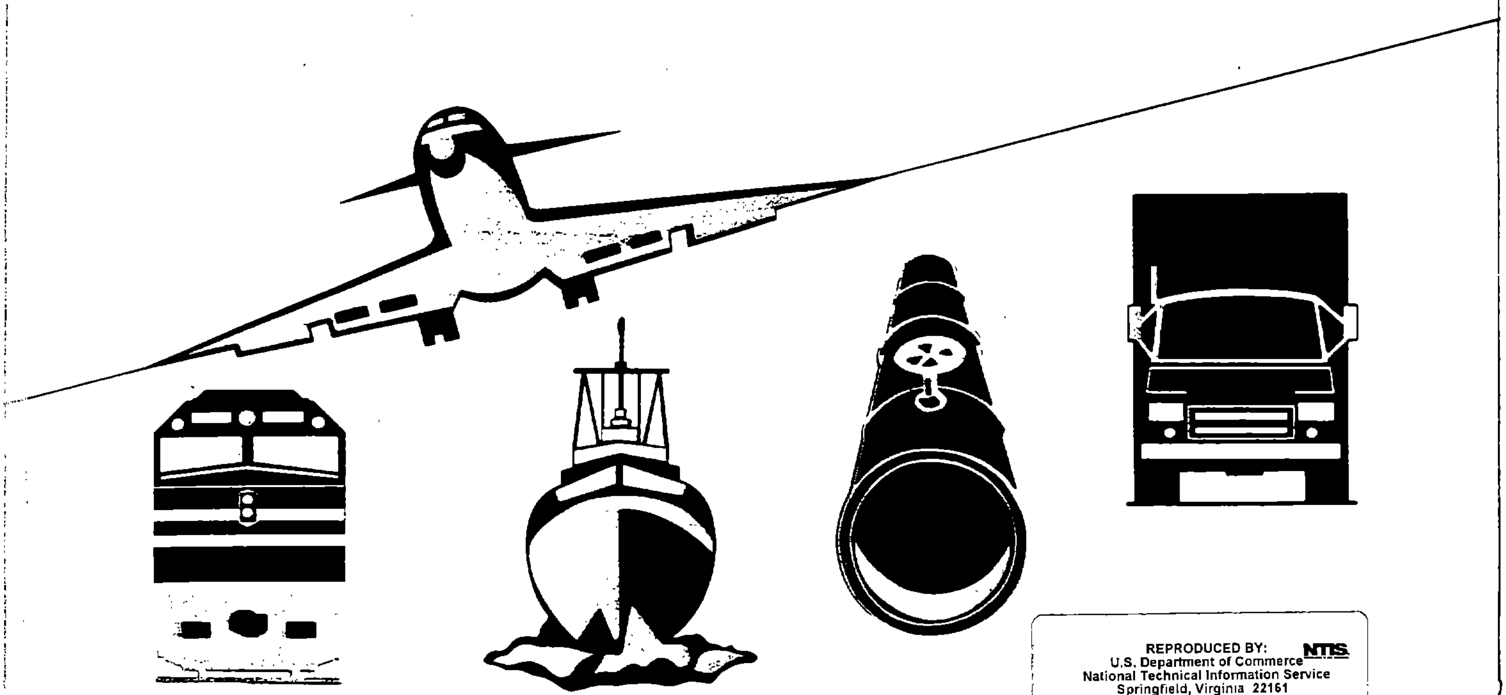

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16. Abstract

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National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

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Date: March 4, 1998

In reply refer to: A-98-9 through -23

Honorable Jane F. Garvey
Administrator
Federal Aviation Administration
Washington, D.C. 20591

On July 6, 1996, at 1424 central daylight time, a McDonnell Douglas MD-88, N927DA, operated by Delta Air Lines Inc., as flight 1288, experienced an engine failure during the initial part of its takeoff roll on runway 17 at Pensacola Regional Airport (PNS) in Pensacola, Florida. Uncontained engine debris from the front compressor front hub (fan hub) of the No. 1 (left) engine penetrated the left aft fuselage. Two passengers were killed, and two others were seriously injured. The takeoff was rejected, and the airplane was stopped on the runway. The airplane, operated by Delta as a scheduled domestic passenger flight under provisions of Title 14 Code of Federal Regulations (CFR) Part 121, with 137 passengers and 5 crew on board, was destined for Hartsfield Atlanta International Airport in Atlanta, Georgia. The JT8D-219 engine was manufactured by Pratt & Whitney. The fan hub was machined, finished, and inspected for Pratt & Whitney by Volvo Aero Corporation in Trollhattan, Sweden, in January 1989. It had accumulated 13,835 cycles at the time of the accident. The service life, or "safe life," of this fan hub was 20,000 cycles.

The National Transportation Safety Board determined that the probable cause of this accident was the fracture of the left engine's front compressor fan hub, which resulted from the failure of Delta Air Lines' fluorescent penetrant inspection (FPI)[1] process to detect a detectable fatigue crack initiating from an area of altered microstructure that was created during the drilling process by Volvo for Pratt & Whitney and that went undetected at the time of manufacture.

[1] FPI is an inspection technique for checking part and component surfaces for cracks or anomalies. The technique involves applying a penetrant fluid (a low viscosity penetrating oil containing fluorescent dyes) to the surface after the part has been cleaned and allowing it to penetrate into any surface cracks. Excess penetrant is then removed and a "developer" is applied to act as a blotter and draw the penetrant back out of any surface cracks. This produces a fluorescent indication of cracks or anomalies when viewed under ultraviolet lighting.

Contributing to the accident was the lack of sufficient redundancy in the in-service inspection program.[2]

Fan Hub Fracture

The investigation revealed that the left engine fan hub fractured radially in two places within a tierod hole[3] early in the takeoff roll when the airplane was at low speed during normal operation. Metallurgical examination of the microstructure underlying the surface of the tierod hole (closest to the hole wall surface) in the origin areas determined that the material was severely deformed and hard. The appearance of the microstructure suggested high frictional heat. Laboratory analysis indicated that the microstructure contained an oxygen-stabilized layer of recrystallized alpha grains[4] adjacent to the surface of the tierod hole. This indicated that the temperature at the surface of the hole in the damaged area had reached at least 1,200°F, the minimum recrystallization temperature for titanium. Iron was also found in this layer of altered microstructure, both widely dispersed and in a high concentration within small isolated bands.

Although stabilized alpha is often associated with an inclusion in the titanium alloy created during the melting or forging process, it can also be formed during machining operations when tools overheat titanium alloy in the presence of air. The location and appearance of the accident hub's altered microstructure indicated that the deformation was formed by a tool used in creating the tierod hole.

Volvo test drillings conducted after the accident produced altered microstructure in two holes, one of which contained features very similar to the accident hub. Test drilling was conducted using a coolant channel drill,[5] but without coolant and at higher drill revolution and feed speeds to promote tool (drill) breakage and the accumulation of chips in the hole. According to Volvo's report, altered microstructure "can be created during rough [initial] drilling, but not during subsequent boring and honing operations."

According to Volvo, the hole with defect features that most resembled those of the accident hub had a microstructure that was "heavily deformed" and that had a hardness that corresponded "with the values for the failed hub." An analysis determined that the layer of

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[2] National Transportation Safety Board. 1998. *Uncontained Engine Failure, Delta Air Lines Flight 1288, McDonnell Douglas MD-88, N927DA, Pensacola, Florida July 6, 1996.* Aircraft Accident Report NTSB/AAR-98-01. Washington, DC.

[3] The aft end of the fan hub attached to the stage 1.5 disk with 24 tierods that passed through tierod holes drilled in the hub rim.

[4] Recrystallization is a formation of a new grain structure from the structure of the deformed metal.

[5] A coolant channel drill has two internal borings that bring coolant/lubricant to the tip of the drill just behind the cutting lips.

deformed microstructure contained ladder type cracking and "a high concentration of iron from the drilling operation."[6]

Because the high temperature (at least 1,200°F) required to form the altered microstructure could not have existed if coolant were flowing freely over the area, the Safety Board considered the possibility that the coolant channel drill malfunctioned. However, because a complete cessation of coolant flow over the hub would have been readily noticeable by the drill operator, the loss of coolant to the area of the altered microstructure was more likely caused by a brief obstruction to the coolant reaching that particular area, such as would result from chip packing or broken pieces of a drill bit. Therefore, chip packing or wedging, leading to a temporary, localized loss of coolant most likely contributed to the creation of the altered microstructure. Thus, the Safety Board concludes that some form of drill breakage or drill breakdown, combined with localized loss of coolant and chip packing, occurred during the drilling process, creating the altered microstructure and ladder cracking in the accident hub. Based on the number of fatigue striations found in the fatigue fracture region, which was roughly equivalent to the number of the hub's flight cycles, the Safety Board further concludes that the fatigue cracks initiated from the ladder cracking in the tierod hole and began propagating almost immediately after the hub was put into service in 1990.

Analysis of Volvo's Inspection Procedures

A blue etch anodize (BEA)[7] test conducted by the Safety Board on the sectioned accident hub revealed a dark blue indication in the areas of the altered microstructure. However, the accident hub passed BEA and visual inspections at Volvo following the drilling process that created the anomalous microstructure. Although the BEA inspector at Volvo noted on a shop traveler[8] that he observed "manufacturing marks" inside a hole, at a subsequent visual inspection inspectors determined that all the holes conformed to Pratt & Whitney acceptance criteria for surface finish on bolt holes. Postaccident metallurgical analysis confirmed that the surface finish in those areas of the tierod hole was consistent with the surface finish requirements specified by Pratt & Whitney. The Safety Board's examination determined that there was no evidence of excessive machining marks at the surface of the hole. It could not be determined whether the BEA inspector made the notation of "manufacturing marks" because of the different surface finish in the tierod hole (boring marks surrounded by honing marks), because of a different coloration resulting from the BEA inspection process, or for some other reason.

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[6]Drill breakdown, for example, could cause minute parts of the drill to shear off during the drilling process.

[7]The BEA inspection process is unique to titanium and involves a visual inspection of the surface after it is anodized (the part surface is electro-chemically oxidized) for anomalies associated with microstructure changes in the metal.

[8]A shop traveler is a process sheet or record that documents inspections or tasks performed on a component.

The Volvo manager who testified during the Safety Board's public hearing stated that the notation by the BEA inspector of "manufacturing marks" in the hole did not signify that the inspector had observed a BEA discrepancy based on the BEA defect templates in use at the time, and he stated that this notation was only intended to alert inspectors conducting subsequent visual inspections with different inspection criteria. Thus, the Safety Board concludes that although the altered microstructure in the accident hub tierod hole was detectable by BEA inspection methods, Volvo did not identify it as rejectable because the appearance of the tierod hole did not match any of the existing inspection templates showing rejectable conditions.

The failure of the manufacturer's BEA inspection to detect and identify a rejectable condition in the accident hub after the drilling process at Volvo resulted in the postaccident development of and addition of four new templates to assist in identifying microstructural defects similar to the accident hub for use by BEA inspectors. The Safety Board recognizes that the BEA inspection process places interpretive demands on inspectors, that identification of rejectable conditions may still not be complete, and that templates of defect indications are added when they are encountered and identified. The Safety Board concludes that although the additional templates will assist BEA inspectors in detecting potential defects similar to the one that existed on the accident hub, this accident suggests that there may be additional rejectable conditions that have not yet been identified. The Safety Board is concerned that these problems may not be unique to parts manufactured by Pratt & Whitney. Therefore, the Safety Board believes that the FAA should form a task force to evaluate the limitations of the BEA and other postmanufacturing etch processes and develop ways to improve the likelihood that abnormal microstructure will be detected. In so doing, it may be appropriate to consider whether any part of these processes can be automated, so as to minimize the possibility of human error.

When Pratt & Whitney approved Volvo's request to use a coolant channel drill, this change was approved because Pratt & Whitney's engineering data indicated that changes in drilling operations were "insignificant" as long as subsequent boring and honing operations were carried out to a depth of at least .010 inch to remove material (including defects) created by the drilling phase. The total depth of material removed from the tierod hole after drilling on the accident hub was about .0185 inch. Metallurgical examinations conducted by the Safety Board after the accident indicated that the total depth of the altered microstructure created by the drill was about .024 inch, more than twice the depth anticipated by the .010-inch limit set by Pratt & Whitney. The Safety Board concludes that drilling damage in this accident hub extended much deeper into hole sidewall material than the depth previously anticipated by Pratt & Whitney. Thus, the Safety Board believes that the FAA should inform all manufacturers of titanium rotating engine components of the potential that current boring and honing specifications may not be sufficient to remove potential defects from holes and ask them to reevaluate their manufacturing specifications and procedures with this in mind.

Failure of Delta Maintenance to Detect Cracking in the Accident Hub

On October 27, 1995, Delta's maintenance facility in Atlanta, Georgia, performed an FPI on the accident hub. This inspection, conducted 1,142 cycles before the accident, was part of overhaul work recommended in Pratt & Whitney's engine shop manual for hubs disassembled from engines before reaching their "safe life" limits.

Postaccident metallurgical examinations conducted by the Safety Board indicated that based on the striation count, at the time of the last FPI, the crack on the aft hub surface adjacent to the tierod hole was about 0.46 inch long and that this crack extended about 0.90 inch within the tierod hole, for a total surface length of 1.36 inches. The FAA's review of FPI processes at Delta concluded that based on reliability data collected by the Nondestructive Testing Information Analysis Center (NTIAC), a visible crack of this size should have been detectable with both a probability of detection and confidence level exceeding 95 percent. The crack was well above the minimum detection length of 0.10 inch as calculated by the NTIAC's Nondestructive Evaluation Capabilities Data Book,[9] and the 0.08-inch and 0.10-inch range suggested in the FAA's December 14, 1990, Titanium Rotating Components Review Team (TRCRT) report. Therefore, the Safety Board concludes that the crack was large enough to have been detectable during the accident hub's last FPI at Delta.

The Safety Board considered the possibility that the crack was not visible during the FPI at Delta. The Safety Board's investigation found that there are a number of ways in which the effectiveness of the FPI process could have been compromised by improperly performed or inadequate procedures. The Safety Board also considered the possibility that the crack was visible at the time of the FPI, but that the FPI inspector either overlooked it or discounted it as insignificant.

Part Cleaning, Drying, Processing, and Handling

The FAA's postaccident report of an August 1996 inspection of the FPI process used by Delta indicated that there was no assurance that parts received by FPI operators were "clean enough for an adequate FPI." The FAA report also noted that cleaning personnel were not made aware of the "criticality of the engine components and the end purpose for which these components were being cleaned." The inspector who inspected the accident hub indicated that he frequently had to send parts back for additional cleaning. The Safety Board recognizes that following the FAA's technical review of Delta's FPI process, Delta indicated that it was providing cleaning personnel with training to emphasize different cleaning procedures for critical parts, especially those being prepared for FPI, and that it was working with engine manufacturers to develop cleaning standards for specific parts. However, the Safety Board is concerned that similar shortcomings may exist at other maintenance facilities performing FPIs.

At the conclusion of the cleaning process in preparation for an FPI at Delta, parts were immersed in a "hot water rinse" and flash dried. Because the dye penetrant applied later in the process has an oil base, any water remaining in cracks would block entry of the dye into those areas. For the flash drying process to be effective, the part must be heated to the temperature of the water, which must be kept at a temperature of between 150° and 200°F, according to Pratt &

[9]See "Nondestructive Evaluation Capabilities Data Book," Published by the NTIAC, Texas Research Institute Austin, Inc. DB-95-02, May 1996.

Whitney's Overhaul Standard Practices Manual (OSPM) and Delta's Process Standard. A temperature measuring device was not used to determine whether parts had reached the temperature of the water. Rather, according to a Delta representative, operators determined that parts had reached the proper temperature by "feel" and that the water temperature was checked on a weekly basis. After the accident and the FAA inspection, Delta implemented changes requiring more frequent checks of the water temperature.

Delta's director of compliance and quality assurance testified at the public hearing that flash drying may not be effective in areas where water is trapped in areas "that you can't readily see or flaws...." A representative of a company that produces FPI hardware and chemicals testified that "it's absolutely imperative that the parts come to the process clean and dry." Another witness from a company that provided Delta with chemicals for the FPI process stated that the effectiveness of flash drying depends on the depth of the crack. "If it's a fairly deep crack...it's doubtful whether you're going to remove that [water] from a fatigue crack," the chemical company witness stated. Although it could not be conclusively determined whether water trapped in the crack at the time of the FPI rendered the crack undetectable by this method, the Safety Board is concerned that a number of experienced practitioners in the field believe that such a potential exists when flash drying is the only drying method used. The Safety Board concludes that significant questions exist about the reliability of flash drying in removing water from cracks.

With regard to the processing of parts after drying, specifically, the application of developer powder, the Safety Board is concerned that when only a spray gun applicator was used, the powder did not cover the hole walls along the full depth of the hole. The Safety Board is further concerned that even using a more focused application tool, such as a squeeze bulb, the geometry of the hub may be such that full coverage of hole walls may never be possible. Although in this case that deficiency would not have prevented detection of the crack (because there was also a sizable crack on the aft face of the hub), under other circumstances this incomplete coverage may result in nondetection of an otherwise detectable crack. Therefore, the Safety Board concludes that better techniques are needed to ensure the fullest possible coverage of dry developer powder, particularly along hole walls.

Safety Board observers also found that Delta had no formal logging procedure to identify parts ready for inspection (inspection must occur within 2 hours of the application of the developer powder and indications found after 1 hour are considered questionable). Delta representatives indicated that shop personnel relied on a "group knowledge" of how long a part had been ready for inspection.

The time between application of the developer and inspection must be controlled to maximize the brilliance of indications (which increases over time), yet ensure that sufficient dye penetrant remains in the defect for diagnostic activities. Delta inspectors described a method for part tracking in which they coordinated with processors to control the flow of parts so that the time limit would not be exceeded. This informal system would have been vulnerable to error from the difficulty of estimating how long an inspection of the part will take inside the booth, worker distraction, and the potential for the loss of collective knowledge during shift turnover.

Thus, it could not have been possible for Delta personnel to consistently adhere to the development time requirements using this system or to know exactly how long a part had been ready for inspection. The Safety Board is concerned that Delta had timing requirements in its process standard but failed to provide its personnel with a way to adhere to them. Thus, there is no assurance that the accident hub was inspected within the limits set forth in the process standard. Although it could not be conclusively determined whether this played a role in the nondetection of the crack in the accident hub, the Safety Board concludes that the absence of a system that formally tracks the timing of the movement of parts through the FPI process was a significant deficiency. The Safety Board notes that after the accident, Delta implemented a procedure to record part development times on a status board that formalizes part tracking and adherence to time requirements. However, the Safety Board is concerned that other operators and repair stations may not have adequate methods to positively identify the status of parts processed for FPIs.

During the FPI process at Delta, hubs are placed aft-side down on a plastic disk to keep them from contacting the rollers on the FPI line during inspection. Processors and inspectors used their hands to lift and turn the hub on the plastic disk to gain access to the aft-side and interior. During these lifting actions, it would have been difficult for personnel to ensure that they were not touching the hub in an area with an indication, particularly on the aft-face. FPI experts testified at the public hearing that penetrant could be rubbed off during handling. If penetrant was prevented (by dirt or water) from fully entering the crack, then rubbing off the surface penetrant would probably have removed any indication of the crack. But even if penetrant was in the crack, loss or distortion of penetrant at the surface could have resulted in an ill-defined indication, thus making the crack more difficult to detect. Although the extent to which it contributed to the nondetection of the crack could not be determined, the manual handling of the hub at Delta during the processing and inspection of the accident hub increased the opportunity for smearing of an indication on the aft-face. The Safety Board notes that after the accident, Delta advised its FPI personnel to minimize manual handling of hubs and to use support equipment, such as an overhead hoist, in the inspection booth.

The Safety Board previously addressed manual handling and methods to support parts during FPI following a July 19, 1989, accident at Sioux City, Iowa, involving a United Airlines DC-10-10 airplane. That accident was also caused by a crack in a critical rotating engine part.[10] The Safety Board report on that accident stated

> It is possible that the inspector...did not rotate the disk, as it was suspended by a cable, to enable both proper preparation and subsequent viewing of all portions of the disk bore, particularly the area hidden by the suspension cable/hose.

The Safety Board is concerned that deficiencies in the methods for handling critical rotating parts during FPI have been identified in this accident and in the United Airlines accident

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[10] National Transportation Safety Board. 1990. *United Airlines Flight 232, McDonnell Douglas DC-10-10, Sioux City Gateway Airport, Sioux City, Iowa, July 19, 1989.* Aircraft Accident Report NTSB/AAR-90/06. Washington, DC.

in Sioux City, Iowa. The Safety Board concludes that FPI indications remain vulnerable to manual handling, and fixtures used to support the part during inspection may obstruct inspector access to areas of the part.

Further, the Safety Board concludes that one or more procedural deficiencies in the cleaning, drying, processing, and handling of the part might have reduced or prevented the effectiveness of Delta's FPI process in revealing the crack. The Safety Board also concludes that the potential deficiencies identified in the Delta FPI process may exist at other maintenance facilities and be, in part, the reason for the failure to detect cracks in other failed engines identified in this investigation. Therefore, the Safety Board believes that the FAA should establish and require adherence to a uniform set of standards for materials and procedures used in the cleaning, drying, processing, and handling of parts in the FPI process. In establishing those standards, the FAA should do the following:

1. Review the efficacy of drying procedures for aqueously cleaned rotating engine parts being prepared for FPIs;
2. Determine whether flash drying alone is a sufficiently reliable method;
3. Address the need to ensure the fullest possible coverage of dry developer powder, particularly along hole walls;
4. Address the need for a formal system to track and control development times; and
5. Address the need for fixtures that minimize manual handling of the part without visually masking large surfaces of the part.

Lack of a Formal Method to Ensure Completeness of Search and Diagnostic Followup

To detect the crack on the aft-face of the hub, the inspector would have had to first detect a bright fluorescent green indication (if there was such an indication) against a dark purple background.[11] To detect the indication, the inspector would have had to systematically direct his gaze across all surfaces of the hub. However, systematic visual search is difficult and vulnerable to human error. Research on visual inspection of airframe components, for example, has demonstrated that cracks above the threshold for detection are missed at times by inspectors because they fail to scan an area of a component.[12] Delta FPI inspectors described inspecting major areas on the -219 hub in the same order each time. Although this technique was variable among inspectors and vulnerable to omission, it would help ensure that major areas of the hub were not missed. However, it is possible that the inspector examined the aft-face of the hub but did not look at the specific area containing the indication near the tierod hole.

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[11]The brilliance of an indication is affected by the crack size and amount of penetrant in the defect. Dye penetrant contamination in the work area, processing errors, and methods used to handle and move hubs during the FPI process can also decrease the brilliance of an indication and can affect the inspector's ability to detect a crack.

[12]Department of Transportation. 1996. *Visual Inspection Research Project Report on Benchmark Inspections. Final Report, October 1996.* DOT/FAA/AR-96/95. Washington, DC. This research group advocated development of NDI reliability models that acknowledge a background miss rate unrelated to crack length to more accurately model the observed data.

Interruption is an inherent part of the FPI process, and the inspector would have interrupted his visual search several times to conduct diagnostic evaluations on detected indications and to reposition the hub. It is possible that the inspector failed to resume his search at the last location examined and that he was not aware of this because of the size and complexity of the part.[13] In studies of airframe inspectors, some have failed to detect defects because they did not resume their inspection at the appropriate location after stopping to move equipment.

It is also possible that the inspector detected an indication at the location of the crack but forgot to diagnose, or reinspect, the location. If inspectors had a method to document examined areas and locations requiring followup diagnosis, the inspector's dependency on memory would be reduced. A system in which an inspector could insert plastic markers into holes that have been inspected and found to be defect-free would serve as a mechanical checklist for the inspector and document the progress of the inspection across the part. Such a system would also reduce the opportunity for human error in other procedural inspections, such as eddy current inspections[14] of rivets or holes.

Nondestructive testing (NDT)[15] inspections of critical rotating parts for small flaws are vulnerable to error in visual search and are dependent on the inspector's memory to ensure that an exhaustive search and adequate followup has been conducted. Accordingly, the Safety Board concludes that an inadvertent failure of the inspector to systematically search and complete followup diagnosis when necessary on all surfaces of the hub might have caused the inspector to overlook the crack. Therefore, the Safety Board believes that the FAA should require the development of methods for inspectors to note on the part or otherwise document during an NDT inspection the portions of a critical rotating part that have already been inspected and received diagnostic followup to ensure the complete inspection of the part.

Low Expectation of Finding a Crack and Decreased Vigilance

FPI inspectors are required to diagnose each detected indication to determine if it is a crack because a crack is reason to reject the part. But not every indication is a crack, and most preliminary indications are later found not to be cracks. The inspector who inspected the accident hub stated that he could not recall ever having detected a crack on a -219 hub, and the inspector's supervisor stated that he was not aware that cracks had ever been found on a -219 hub at Delta. Therefore, the inspector's experience diagnosing indications on -219 hubs consisted of a series of false indications. Although the inspector stated that he approached a part as if it had a

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[13]It is also possible that the glare associated with the use of white light to diagnose indications contributed to this omission because this process caused his eyes to lose dark adaptation.

[14]Eddy current inspections measure fluctuations in an alternating magnetic field around a part generated by a transducer carrying an alternating current. Eddy current inspections are used to locate surface and near-surface defects.

[15] NDT methods are those that do not damage or significantly alter the component being tested during inspection.

crack to detect, his experience with indications on -219 hubs most likely biased his expectation of confirming that an indication was a crack, especially if the indication was not clearly defined. Therefore, the Safety Board concludes that a low expectation of finding a crack in a -219 series fan hub might have caused the inspector to overlook or minimize the significance of an indication.

A low expectation of finding a crack might also have decreased the inspector's vigilance. Further, research on vigilance suggests that performance decreases with increasing inspection time.[16] However, data to support this conclusion in the aviation inspection domain are inconclusive. In addition, a recent study of eddy current inspection of airframe skin panels found no relationship between inspection duration and probability of defect detection.[17] In any event, no evidence from this investigation exists to evaluate how inspection duration and the adequacy of breaks (the inspector stated he took frequent breaks) affected the inspection of the accident hub. The inspector who inspected the accident hub characterized the FPI process as tedious and monotonous and stated that he spent about 75 percent of his shift inspecting parts. He also stated that inspection of a -219 hub typically took about 40 minutes to 2 hours, depending on the number of indications detected.

The Safety Board concludes that the duration of inspections and the amount and duration of rest periods may indeed affect inspector performance, but this potential has not been adequately studied in the aviation domain. Therefore, the Safety Board believes that the FAA should conduct research to determine the optimum amount of time an inspector can perform NDT inspections before human performance decrements can be expected.

Inadequate Diagnostic Techniques or Controls

It is also possible that the inspector detected an indication at the location of the crack but did not properly complete the followup diagnostic procedure. Diagnostic procedures must be consistently performed and the appropriate time periods must be allowed for redevelopment to ensure that a true defect is not allowed to pass. Delta's Process Standard for conducting FPIs directed inspectors to wait at least 5 minutes to confirm that an indication had not reappeared after developer was applied during the bleedout procedure. As discussed above, there was no formal method for the inspectors to track these indications and to ensure that they were reinspected after the required redevelopment period. Further, no formal method was in place to ensure adherence to the redevelopment time period. The Safety Board anticipates that in establishing the uniform set of standards (recommended above), the FAA will recognize the need for a formal system for measuring and recording development times listed in their process standards for FPI.

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[16] Drury, C. G. 1992. *Inspection Performance, Handbook of Industrial Engineering*. New York.

[17] Department of Transportation. 1992. *Reliability Assessment at Airline Inspection Facilities, Volume III: Results of an Eddy Current Inspection Reliability Experiment. May 1995. Final Report.* DOT/FAA/CT-92/12, III. Washington, DC.

Adequacy of Inspector Training and Proficiency

The Safety Board addressed the issue of NDT inspector training in a previous accident investigation of an uncontained engine failure.[18] In that accident, the Safety Board concluded that a ½-inch crack was present during the last inspection of the disk that would have been detected if proper magnetic particle inspection (MPI) methods had been applied. The Safety Board noted that inspectors at the engine's repair station had trained each other and that the manufacturer had recommended that the repair station develop a formal initial and recurrent training program. In contrast, the Delta FPI inspector had completed a formal training program that included written and practical examinations and his training was consistent with industry standards. However, because this accident revealed that a crack was not detected at a repair facility that followed industry guidance, the Safety Board issued Safety Recommendation A-96-77 on July 29, 1996, asking the FAA to

> Review and revise, in conjunction with the engine manufacturers and air carriers, the procedures, training (including syllabi and visual aids) and supervision provided to inspectors for performing FPI and other nondestructive testing of high-energy rotating engine parts, with particular emphasis on the JT8D-200 series tierod and stress redistribution holes.

The Safety Board classified this recommendation "Open—Acceptable Response" in February 1997, pending final FAA action after the FAA stated that it had inspected Delta's FPI facility and concluded that the airline "had the proper guidance for training and qualifying personnel" in NDT and FPI. The Safety Board's decision was also based on FAA plans to have its FPI Review Team visit six FPI facilities, at a rate of two facilities per month. After the inspections, the FAA stated that it would issue a report and determine what course of action, if any, needed to be taken. The FAA stated that it would also evaluate other facilities that perform FPI and other NDT procedures to determine whether systemic problems existed. The FAA has completed these inspections, but the report has not yet been issued.

A human factors expert testified at the public hearing on this accident that methods have been identified to augment training in inspection. These methods include incremental guidance for specific inspection skills and feedback guidance to inspectors during training. As the FAA completes action on A-96-77, the Safety Board anticipates that the FAA will consider these methods to improve inspector performance.

After the FAA's August 1996 review of Delta's FPI facility, the FAA recommended that written and proficiency examinations be required during inspector recertification. Delta responded to the recommendation by requiring that inspectors pass a written examination on FPI procedural knowledge and receive training to proficiency on a practical examination on a set of 10 sample parts. The Safety Board agrees with the FAA that additional and more frequent

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[18] National Transportation Safety Board. 1996. *Uncontained Engine Failure/Fire, ValuJet Airlines Flight 597, Douglas DC-9-32, N908VJ, Atlanta, Georgia, June 8, 1995.* Aircraft Accident Report NTSB/AAR-96/03. Washington, DC.

evaluation of inspectors is needed to ensure that inspectors are qualified to do their job. Written examinations provide information about an inspector's knowledge of the inspection process and procedures. Proficiency examinations like the one administered at Delta determine whether the inspector can apply the inspection procedures and interpret the results using a limited set of test pieces or actual parts. However, the effectiveness of an inspection involving visual search, like FPI, depends on the inspector's skills in visual search and detection, which cannot be adequately evaluated using written exams and practical tests that do not evaluate the ability of an inspector to detect indications using a sample of representative parts with and without defects. It would be beneficial to evaluate the inspector's skills to detect defects on the line, however, because defects that are missed on actual parts can go undetected. Important feedback information required to determine inspector sensitivity is not available.

The Safety Board concludes that because of the potentially catastrophic consequences of a missed crack in a critical rotating part, testing methods that evaluate inspector capabilities in visual search and detection and document their sensitivity to detecting defects on representative parts are necessary. Such methods would require an inspector to examine several parts, some containing defects and some without, which are representative of those tested on the line. In addition, the defects provided should range in size from small at the threshold for the inspection method to large and well within the method's capabilities. A test of this type would provide an indication on the capabilities of the inspector unlike practical tests on only a few samples or that involve training to proficiency. Further, it would facilitate a comparison of how different inspectors perform and if administered on a frequent basis provide a way to track inspector performance and focus recurrent training. Therefore, the Safety Board believes that the FAA should, in conjunction with industry and human factors experts, develop test methods that can evaluate inspector skill in visual search and detection across a representative range of test pieces, and ensure proficiency examinations incorporate these methods and are administered during initial and recurrent training for inspectors working on critical rotating parts.

Because FPI is dependent on several individuals performing multiple procedures, no single reason for the nondetection of the crack in this accident could be identified. The Safety Board concludes that Delta's nondetection of the crack was caused either by a failure of the cleaning and FPI processing, a failure of the inspector to detect the crack, or some combination of these factors.

Adequacy of Inspection Requirements for Critical Rotating Titanium Components

The Safety Board issued comprehensive recommendations following the United Airlines accident in Sioux City, Iowa, in which an in-flight uncontained engine failure led to the loss of the three hydraulic systems that powered the airplane's flight controls. The investigation found that fatigue cracking in the front fan disk originated in a hard alpha inclusion that had formed during the casting of the disk material. Included in the recommendations were Safety Recommendations A-90-89 and -90, which asked the FAA to develop a damage tolerance inspection program for all engine components that, if they failed or separated, posed a significant threat to the structures and systems of airplanes. In response, the FAA formed the TRCRT to assess the quality control procedures used in the manufacture of titanium alloy high-energy rotating components of turbine engines.

The TRCRT final report made several recommendations related to in-service inspections of titanium rotating parts, including using eddy current inspections to supplement FPIs and a requirement to subject such parts to at least two "subsurface inspections" (e.g., ultrasonic)[19] during their cyclic life. However, the implementation schedule for recommendations contained in the TRCRT report was canceled by the FAA following a 1991 industry conference during which industry representatives requested that the schedule be modified. Based on an April 6, 1993, FAA letter to the Safety Board that stated that future action would be taken to "develop implementation schedules commensurate with the needs of the FAA, industry, and the flying public," the Safety Board classified both safety recommendations "Closed—Acceptable Alternate Action" on May 28, 1993. The Safety Board is disappointed that no new schedules were developed and that no further action was taken by the FAA to implement the recommendations in the TRCRT report.

In addition to this accident, several other uncontained engine failures have occurred after the Sioux City accident and the TRCRT report because of fatigue cracking that initiated from various sorts of microstructural conditions created at manufacture.[20] Further, there was also evidence of manufacturing defects in several engines that failed before the Sioux City accident.[21] This accident history demonstrates that a variety of manufacturing anomalies in a variety of locations on engine parts can lead to uncontained failures, and that manufacturing defects are not as rare as might once have been believed. Further, given the loss of life that has resulted from the Sioux City and Pensacola failures, it is also clear that such defects can pose a significant threat to safety.

Most, if not all, of these engine parts were, at the time of manufacture, subjected to one or more nondestructive inspection techniques (such as an etch, ultrasonic inspection, or FPI) designed to detect manufacturing-related flaws and anomalies that may lead to cracking. (Some of the etch and ultrasonic inspections were performed on the rectilinear part [machine forged

[19]Ultrasonic testing is an NDT method in which high-frequency sound waves are introduced to materials to detect surface and subsurface flaws.

[20]A 1993 failure of the HPC stage 3-9 spool in a CF6-80C2 in Los Angeles, California, was attributed to dwell time fatigue initiating an area of aligned alpha colonies in the titanium alloy; a 1995 failure of an Egypt Air CF6-50C2 engine was attributed to a crack originating at a hard alpha inclusion in stage 6 of the HPC 3-9 stage spool; a 1995 failure of a CF6-50C2B engine in Bangkok, Thailand, was attributed to dwell time fatigue resulting from aligned alpha colonies in the disc bore of the 3-9 HPC; and evidence from a 1997 failure of a Canadian Airlines CF6-80C2B6F engine, which is still under investigation, has revealed a microstructural anomaly in the blade slot bottom of the 3rd-stage HPC 3-9 stage spool.

[21]The 1982 failure of a Pan Am JT8D-7 engine was attributed to a crack originating in altered microstructure in a tierod hole, and three CF6 engine failures occurring in 1974, 1979, and 1983 were attributed to cracking originating in hard alpha inclusions.

shape], and not on the final shape,[22] a practice that is no longer being used.) However, none of the flaws and anomalies that existed in those parts were detected, and the parts passed inspection. This demonstrates that the inspection methods used at manufacture can be fallible, and that newly manufactured engine parts may be placed into service containing potentially dangerous flaws.

Further, many of the flawed engine parts were subjected to in-service FPI or ultrasonic inspections after they developed cracks that had propagated to detectable lengths, yet they were not removed from service.[23] Thus, it is clear that detectable cracks in critical rotating engine parts may escape detection, even though the part has undergone in-service nondestructive testing techniques such as FPI. This point is further demonstrated by the ValuJet uncontained engine failure in Atlanta which, although it did not involve a manufacturing defect, again shows that a critical rotating part with a detectable crack can successfully pass through an NDT process (in that case magnetic particle inspection)[24] and be placed back into service. Probability of detection data confirm that even assuming the FPI procedures are properly executed, some detectable cracks will be missed. However, because FPI procedures may not always be properly carried out, there are several additional reasons why a detectable crack may be missed during the FPI process.

The Safety Board concludes that manufacturing and in-service inspection processes currently being used do not provide sufficient redundancy to guarantee that newly manufactured critical rotating titanium engine parts will be put into service defect-free and will remain crack-free through the service life of the part. The Safety Board agrees with the TRCRT conclusion that

> [based on the] frequency of occurrence of titanium metallurgical defects, the difficulty of detecting defects in titanium,...the many sources of defects, errors and damage, recent developments in the engineering science of fracture mechanics (crack propagation) analysis...the random approach of inspections of opportunity is not adequate, and can no longer be justified.

In light of the above, the Safety Board is especially concerned that the FAA's initial and recurring inspection program, as outlined in Airworthiness Directive (AD) 97-02-11 and a subsequent final rule addressing the intent of Safety Recommendation A-96-74 (by taking into account the potential for microstructural defects produced by standard drills after a "major event such as tool breakage"), does not include mandatory or fixed-interval repetitive inspections for the remaining population of 2,272 fan hubs urged in Safety Recommendation A-96-75.

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[22]For example, the parts involved in the Sioux City, Egypt Air, and Canadian Airlines accidents were etched only in their rectilinear shape and were subjected to FPI in their final shape.

[23]In addition to the fan hub involved in this accident, the parts involved in the 1989 Sioux City, 1995 Egypt Air, 1982 Pan Am, 1995 Thailand, and 1997 Canadian Air accidents all underwent in-service FPI.

[24]MPI is an NDT testing method that uses part or surface magnetization to locate surface and subsurface effects.

The Safety Board is concerned that JT8D-200 series fan hubs with more than 4,000 CSN may not receive FPI and eddy current inspections when these fan hubs are in the shop because there is no requirement to disassemble hubs to the piece-part level. In addition, AD 97-02-11 imposed no inspection requirement before retirement at 20,000 cycles in service (CIS) on fan hubs that have accumulated over 10,000 CIS before March 5, 1997, which constitutes a large percentage of all JT8D-200 series fan hubs. As such, AD 97-02-11 does not require the population of JT8D-200 series fan hubs with holes produced with standard drills or hubs with no machining or dimensional anomalies to be inspected unless the engine is disassembled to the piece-part level. This approach remains unacceptable.

However, the Safety Board's concern is not limited to JT8D-200 series fan hubs, but extends to all critical rotating titanium engine components. The Safety Board concludes that all critical rotating titanium engine components are susceptible to manufacturing flaws and resulting cracking and uncontained engine failures that could potentially lead to catastrophic accidents. Therefore, the Safety Board believes that the FAA should require that all heavy rotating titanium engine components (including the JT8D-200 series fan hubs) receive appropriate NDT inspections (multiple inspections, if needed) based on probability of detection data at intervals in the component's service life, such that if a crack exists, but is not detected during the first inspection, it will receive a second inspection before it can propagate to failure. In developing the inspection intervals, the Safety Board urges the FAA to assume that a crack may begin to propagate immediately after being put into service, as occurred in this accident and the United Airlines accident at Sioux City.

The Safety Board recognizes that all necessary probability of detection data and crack propagation rates may not be immediately available, and may have to be developed for some components. Therefore, the Safety Board believes that the FAA should require, as an interim measure, pending implementation of Safety Recommendation A-98-19, that critical rotating titanium engine components that have been in service for at least 2 years receive an FPI, eddy current, and ultrasonic inspection of the high-stress areas at the engine's next shop visit or within 2 years from the date of this recommendation, whichever occurs first.

These recommendations supersede Safety Recommendations A-96-74 and A-96-75, which the Safety Board now classifies "Closed—Unacceptable Action/Superseded."

Maintenance Deficiencies

During the preflight inspection the first officer found a small amount of oil on the bullet nose of the left engine and two rivets missing from the left wing. The oil that was found on the bullet nose could not have been related to the hub failure, and the missing rivets were from an outboard section of the wing. Therefore, the Safety Board concludes that these were not factors in the subsequent engine failure.

However, the Safety Board is concerned that the flightcrew did not request maintenance action before departure from Pensacola and that flightcrews may generally be reluctant to request maintenance at airports without company maintenance facilities because the reporting process and arranging for contract maintenance may result in delays. In this instance, the captain's deferral of a maintenance check of the oil leak until after arrival in Atlanta and his failure to ensure that maintenance action was taken on the missing rivets appear to have been contrary to guidance contained in Delta's Flight Operations Manual (FOM), which required flightcrews to notify Delta maintenance personnel of maintenance irregularities, or fluid leaks, at the gate. However, the flightcrew's decision was later supported by Delta management. This suggests that Delta management does not agree that fluid drops on the bullet nose or two missing rivets constitute maintenance irregularities.

Thus, the Safety Board concludes that there is a lack of clarity in written guidance in the FOM to Delta flightcrews on what constitutes maintenance "discrepancies" and "irregularities" and when to contact maintenance personnel and to log anomalies. Therefore, the Safety Board believes that the FAA should require Delta Air Lines to review its operational procedures, with special emphasis on nonmaintenance stations, to ensure that flightcrews have adequate guidance about what constitutes a maintenance irregularity or discrepancy (including the presence of fluid drops in unusual locations) before departure, and that following this review Delta should, contingent on FAA approval, amend its FOM to clarify under what circumstances flightcrews can, if at all, make independent determinations to depart when maintenance irregularities are noted. Further, the Safety Board is concerned that similar situations may be encountered by flightcrews at other airlines. Therefore, the Safety Board believes that the FAA should have its principal operations inspectors review these policies and procedures at their respective operators to clarify, if necessary, these flightcrew responsibilities.

Crew Actions and Survival Factors

Immediately following the engine failure, the circumstances in the aft cabin were markedly different than those in the forward cabin. The aft flight attendants were presented with structural damage, serious injuries, and an engine fire, any one of which was sufficient to initiate an evacuation pursuant to Delta's policy and procedures. In contrast, the cockpit crew and forward flight attendant were unaware of these circumstances and, based on the absence of any indications of fire, the captain determined that an evacuation was not warranted. Unaware that passengers were evacuating, the captain did not shut down the engines until the first officer alerted him to do so after having walked through the cabin to assess the situation.

The interphone system was inoperative at the critical moment when decisions were being made by the aft flight attendants to evacuate and by the captain not to evacuate. Thus, neither of these decisions, nor the information on which they were based, could be immediately communicated to crewmembers at the opposite end of the airplane. By the time emergency electrical power was restored to the interphone and the first officer again attempted to contact the aft flight attendants, the flight attendants were no longer in a position to, and would not have been expected to, respond to calls over the interphone because they were carrying out the evacuation and attending to injured passengers.

The Safety Board concludes that neither the aft flight attendants' decision to evacuate nor the captain's decision not to evacuate was improper in light of the information each of them had available at the time. However, the Safety Board is troubled by the lack of communication among crewmembers in the front and back of the airplane. Specifically, the Safety Board is concerned that crewmembers in the cockpit were unaware that emergency conditions existed and an evacuation was ongoing in the rear of the airplane. Even if this information would not have affected the captain's determination not to evacuate the entire airplane, at the very least it likely would have prompted him to immediately shut down the engines to minimize the hazards to those passengers who were evacuating.

The Safety Board has long been concerned about the difficulties that can arise when normal means of communication (interphone and/or public address systems) become unavailable during an emergency situation, when they generally are most needed. Evacuation decisions, which must often be made very quickly, should be based on the most complete information possible about the condition of the airplane and possible hazards. As noted in an accident report on the December 20, 1995, accident involving Tower Air flight 41 at JFK International Airport,[25] "positive communications are essential to coordinate the crew's response, even if the decision is not to evacuate."

In 1972 and 1981 the Safety Board recommended that the FAA require independently powered evacuation alarm systems. However, at that time, the FAA determined that the cost of installing such alarm systems "would far outweigh any identifiable safety benefits." Thus, in most airplanes today, if there is a loss of airplane electrical power, crewmembers and passengers in one part of the airplane may not be aware of an evacuation that is occurring in another part of the airplane. Because a decision to evacuate generally indicates that there may be a hazard to passengers if they remain on board, the Safety Board remains concerned that the lack of an independently powered evacuation alarm system on most airplanes is a significant safety deficiency that should be corrected.

The Safety Board concludes that every passenger-carrying airplane operating under 14 CFR Part 121 should have a reliable means to ensure that all crewmembers on board the airplane are immediately made aware of a decision to initiate an evacuation. Therefore, the Safety Board believes that the FAA should require that all newly manufactured passenger-carrying airplanes operated under 14 CFR Part 121 be equipped with independently powered evacuation alarm systems operable from each crewmember station. The FAA should also require carriers operating airplanes so equipped to establish procedures, and provide training to flight and cabin crews, regarding the use of such systems. The issue of retrofitting existing airplanes with such systems will be addressed in the Safety Board's upcoming evacuation study.

As illustrated in this accident, emergency exits are sometimes opened by passengers before any evacuation order has been given or any decision has been reached. It is important for cockpit crews to know that exits have been opened for any reason so that appropriate measures

[25] National Transportation Safety Board. 1996. *Runway Departure During Attempted Takeoff, Tower Air Flight 41, Boeing 747-136, JFK International Airport, New York, December 20, 1995.* Aircraft Accident Report NTSB/AAR-96/04. Washington, DC.

can be taken to minimize the resulting potential hazards to passengers who may be departing the airplane through those exits. The Safety Board is aware that some airplanes, including the MD-88, are equipped with cockpit indicators showing open exits, but the Safety Board concludes that safety could be enhanced if all cockpit crews were immediately made aware of when exits are opened during an emergency. Therefore, the Safety Board believes that the FAA should require that all newly manufactured airplanes be equipped with cockpit indicators showing open exits, including overwing exit hatches, and that these cockpit indicators be connected to emergency power circuits. The issue of retrofitting existing airplanes will be addressed in the Safety Board's upcoming evacuation study.

Finally, the Safety Board is concerned that the overwing exits were opened while the airplane was still moving. The passenger who opened that exit told Safety Board investigators that he was uncertain whether he should open the exit and wished that he had received some guidance as to when it should be opened. The "Passenger Safety Information" card made available to each passenger on the Delta MD-88 illustrates how to open the exits, and states that persons seated in emergency exit seats must be able to "[a]ssess whether opening the emergency exit will increase the hazards to which passengers may be exposed." However, the card does not specifically state when the exit should be opened or describe the conditions under which doing so might increase the hazards to which passengers might be exposed. Nor does the card state that the exit should not be opened until the airplane has come to a stop. The Safety Board concludes that the guidance provided to passengers on Delta Air Lines MD-88s regarding when emergency exits should and should not be opened is not sufficiently specific. The Safety Board is also concerned that guidance provided by other airlines on other airplanes might be similarly vague. The Board will address this issue further in its upcoming evacuation study.

As a result of the investigation of this accident, the National Transportation Safety Board recommends the following to the Federal Aviation Administration:

> Form a task force to evaluate the limitations of the blue etch anodize and other postmanufacturing etch processes and develop ways to improve the likelihood that abnormal microstructure will be detected. (A-98-9)
>
> Inform all manufacturers of titanium rotating engine components of the potential that current boring and honing specifications may not be sufficient to remove potential defects from holes and ask them to reevaluate their manufacturing specifications and procedures with this in mind. (A-98-10)
>
> Establish and require adherence to a uniform set of standards for materials and procedures used in the cleaning, drying, processing, and handling of parts in the fluorescent penetrant inspection process. In establishing those standards, the FAA should do the following:
>
> > Review the efficacy of drying procedures for aqueously cleaned rotating engine parts being prepared for fluorescent penetrant inspections; (A-98-11)

Determine whether flash drying alone is a sufficiently reliable method; (A-98-12)

Address the need to ensure the fullest possible coverage of dry developer powder, particularly along hole walls; (A-98-13)

Address the need for a formal system to track and control development times; (A-98-14) and

Address the need for fixtures that minimize manual handling of the part without visually masking large surfaces of the part. (A-98-15)

Require the development of methods for inspectors to note on the part or otherwise document during a nondestructive inspection the portions of a critical rotating part that have already been inspected and received diagnostic follow up to ensure the complete inspection of the part. (A-98-16)

Conduct research to determine the optimum amount of time an inspector can perform nondestructive testing inspections before human performance decrements can be expected. (A-98-17)

In conjunction with industry and human factors experts, develop test methods that can evaluate inspector skill in visual search and detection across a representative range of test pieces, and ensure proficiency examinations incorporate these methods and are administered during initial and recurrent training for inspectors working on critical rotating parts. (A-98-18)

Require that all heavy rotating titanium engine components (including the JT8D-200 series fan hubs) receive appropriate nondestructive testing inspections (multiple inspections, if needed) based on probability of detection data at intervals in the component's service life, such that if a crack exists, but is not detected during the first inspection, it will receive a second inspection before it can propagate to failure; assuming that a crack may begin to propagate immediately after being put into service, as it did in the July 6, 1996, accident at Pensacola, Florida, and in the July 19, 1989, United Airlines accident at Sioux City, Iowa. (A-98-19)

Require, as an interim measure, pending implementation of Safety Recommendation A-98-19, that critical rotating titanium engine components that have been in service for at least 2 years receive a fluorescent penetrant inspection, eddy current, and ultrasonic inspection of the high-stress areas at the engine's next shop visit or within 2 years from the date of this recommendation, whichever occurs first. (A-98-20)

Require Delta Air Lines to review its operational procedures, with special emphasis on nonmaintenance stations, to ensure that flightcrews have adequate guidance about what constitutes a maintenance irregularity or discrepancy (including the presence of fluid drops in unusual locations) before departure, and that following this review Delta should, contingent on FAA approval, amend its flight operations manual to clarify under what circumstances flightcrews can, if at all, make independent determinations to depart when maintenance irregularities are noted. Further, the FAA should have its principal operations inspectors review these policies and procedures at their respective operators to clarify, if necessary, these flightcrew responsibilities. (A-98-21)

Require that all newly manufactured passenger-carrying airplanes operated under 14 Code of Federal Regulations Part 121 be equipped with independently powered evacuation alarm systems operable from each crewmember station, and establish procedures and provide training to flight and cabin crews regarding the use of such systems. (A-98-22)

Require that all newly manufactured airplanes be equipped with cockpit indicators showing open exits, including overwing exit hatches, and that these cockpit indicators be connected to emergency power circuits. (A-98-23)

Chairman HALL, Vice Chairman FRANCIS, and Members HAMMERSCHMIDT, GOGLIA, and BLACK concurred in these recommendations.

By: Jim Hall
Chairman

National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

CORRECTED COPY

Date: March 6, 1998

In reply refer to: A-98-27 through -33

Honorable Jane F. Garvey
Administrator
Federal Aviation Administration
Washington, D.C. 20591

On September 7, 1997, Canadian Airlines International flight CP30, a Boeing 767-300ER airplane, equipped with General Electric Aircraft Engines (GEAE) CF6-80C2B6F engines, experienced an uncontained failure[1] of the high-pressure compressor (HPC) stage 3-9 spool (figure 1) in the No. 1 (left) engine during takeoff at Beijing, China. The airplane was on a regularly scheduled passenger flight from Beijing to Vancouver, Canada. The flightcrew reported that during the initial part of the takeoff as the throttles were advanced, the No. 1 engine surged. This was followed by a fire warning in the cockpit and significant vibration in the airplane. The crew rejected the takeoff at a speed of about 20 knots and discharged both fire bottles for the No. 1 engine. The engines were shut down, and the airplane was towed to the terminal without further incident. The 199 passengers and 10 crewmembers on board sustained no injuries.

The examination of the engine revealed substantial damage in the area of the HPC. The HPC case was ruptured aft of the stage 2 variable stator vanes. The stage 3 disk portion of the HPC stage 3-9 spool had separated from the remainder of the spool, exited the engine, and broken into three pieces, all of which were recovered. The No. 1 engine's right-hand thrust reverser cowl had a 2-inch by 1-inch cut in the skin. The reported fire was caused by fuel that had leaked from a line that supplies pressure to the active clearance control[2] valve, which was severed by one of the liberated pieces of the 3rd-stage disk.

[1] An uncontained engine failure occurs when an internal part of the engine fails and is ejected through the cowling.

[2] The active clearance control system provides air to externally cool the turbine cases to minimize the thermal growth of the cases that reduces the gaspath leakage between the turbine blade tips and turbine case air seals to improve an engine's fuel efficiency.

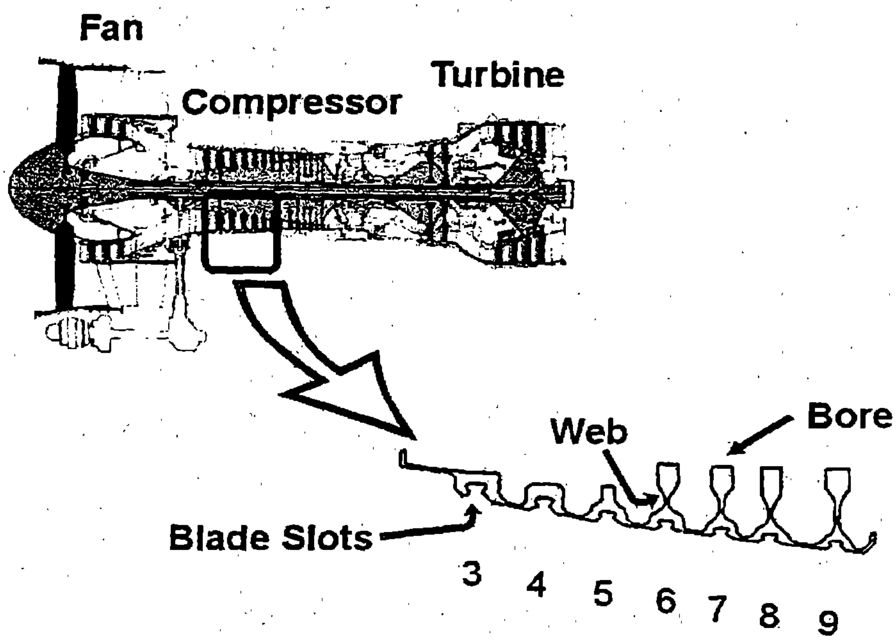

Figure 1.—Typical 3-9 spool in cross section.

The investigation of this incident is under the direction of the Transportation Safety Board of Canada (TSB). The National Transportation Safety Board, under the provisions of Annex 13 to the International Convention on Civil Aviation, is assisting the TSB with its investigation. Information gathered in the investigation thus far raises serious concerns that warrant action by the Federal Aviation Administration (FAA).

The HPC stage 3-9 spool is a rotor component that is composed of disks joined together with integral spacer segments and end flanges and is made from Ti-6242 titanium alloy.[3] The incident spool, part number 1333M66G01, was a two-piece assembly made by GEAE in 1989.[4] According to maintenance records, the spool had accumulated a total of 25,653 hours and 4,744 cycles since new (CSN). The front portion of the spool was forged by Schlosser Forge Company

[3]Titanium-based alloy containing 6 percent aluminum, 2 percent tin, 4 percent zirconium, and 2 percent molybdenum.

[4]The stage 3-9 spool was first manufactured by GEAE in 1971 for the CF6-50 engine as a one-piece spool that was forged from a 16-inch diameter billet. (A billet is a semifinished round product from which a part is forged. The required diameter of a billet is achieved by hot-working [forging] of an ingot in several stages.) In 1980, the billet diameter was reduced to 13 inches to improve the inspectability and provide for more working of the material during forging. Also around 1980, GEAE began to produce two-piece spools from 12-inch and 13-inch diameter billets. In the two-piece configuration, the front (stages 3 through 5) and rear (stages 6 through 9) portions of the spool are forged separately. The forgings are then machined to a rectilinear shape (which has straight sides and perpendicular corners), welded together, heat treated, and machined to the final shape. Between 1988 and July 1995, GEAE produced two-piece spools that had the front and rear portions of the spool forged from 9-inch and 10-inch diameter billets, respectively. Until 1995, all two-piece spools received a postweld solution heat treatment followed by a slow cool down. In 1995, that process was replaced by a postweld stress-relief process. Also, in July 1995, GEAE started to produce two-piece spools forged from 8-inch diameter billets.

from a 9-inch diameter billet produced by Reactive Metals Incorporated (RMI), and the aft portion was forged by Wyman-Gordon Company from a 10-inch diameter billet produced by Titanium Metals Corporation of America. Both pieces were welded by GEAE, and machined to the final shape by Volvo Aero Corporation, Trollhattan, Sweden.

Metallurgical examination of the 3rd-stage disk of flight CP30's HPC spool was conducted at the TSB's engineering and the Safety Board's materials laboratories. The examination revealed a fatigue fracture that was about 1 ¾-inches long and about ½-inch deep, emanating from an area (not a clear, specific origin) at or near the bottom of a dovetail blade slot. Metallographic examination of numerous sections from the area of the fracture revealed a band of abnormal microstructure that contained predominantly alpha phase (the Ti-6242 alloy outside of the area of abnormal microstructure contained a mixture of approximately equal amounts of alpha and beta phases[5]) and elevated oxygen levels. This band of abnormal microstructure extended from the front to the rear face of the 3rd-stage disk and intersected the bottom of the dovetail slot.

Microprobe and wavelength dispersive analysis of several locations along the band of abnormal microstructure revealed oxygen levels of 0.4 to 0.6 percent. The applicable GEAE specification for Ti-6242 titanium alloy, C50TF39-S4, restricts oxygen content to a maximum of 0.15 percent. A spectrographic chemical analysis of the 3rd-stage disk material away from the fracture area and well outside the band of abnormal microstructure showed that it conformed to the GEAE specification requirements for Ti-6242 alloy. Hardness tests showed that the maximum hardness in the oxygen-rich area was 43 on the Hardness Rockwell C scale (HRC). In comparison, the hardness in other areas of the spool ranged from 29 HRC to 40 HRC (averaging 35 HRC), which, according to GEAE, is typical for premium quality Ti-6242 alloy.[6]

Further, the examination of the fracture surface with a scanning electron microscope revealed that about 80 percent of the fatigue region contained brittle cleavage-like,[7] faceted features with no identifiable fatigue striations, and about 20 percent contained classical fatigue striations. Metallurgists were able to count about 800 classical fatigue striations along a radial line extending through the fatigue region from the dovetail slot bottom to the stage 3 disk bore.

Adequacy of Current In-Service Inspection Techniques for Detecting Cracks

The records for the incident engine show that in October 1994, the engine, including the HPC stage 3-9 spool, was overhauled because of the ingestion of recapped tire fragments into the engine during the takeoff roll. The overhaul was performed by Caledonian Airmotive,[8] Prestwick, Scotland, at 2,758 CSN (1,986 cycles before the incident) and included a fluorescent penetrant

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[5]When titanium takes the crystallographic form known as "alpha phase" (also referred to as a low-temperature titanium phase) it has a hexagonal close-packed crystal structure. When it takes the crystallographic form known as "beta phase" (also referred to as a high-temperature titanium phase) it has a body-centered cubic crystal structure.

[6]Applicable GEAE material specification C50TF39-S4 does not specify a required minimum or maximum hardness level for Ti-6242.

[7]Cleavage refers to the splitting of a crystallized substance along definite crystal planes.

[8]Caledonian Airmotive was subsequently acquired by Greenwich Aviall, and then by GE Caledonian.

inspection (FPI)[9] and an ultrasonic[10] inspection. The maintenance records show that neither the FPI nor the ultrasonic inspection revealed any rejectable indications in the spool.[11]

The investigation revealed that the FPI and ultrasonic inspection techniques performed on the spool in 1994, even when combined with the eddy current inspections,[12] which were subsequently included in the GEAE engine maintenance manual for the inspections of HPC stage 3-9 spools, do not provide 100 percent inspection coverage of the spool. According to GEAE, the currently prescribed manner in which the ultrasonic inspection probe is directed at the spool's disk bore results in several internal "blind spots" that are beyond the coverage capabilities of the ultrasonic inspection technique. The crack that resulted in the uncontained failure of flight CP30's HPC stage 3-9 spool originated from an area located in one of these blind spots. The investigation determined that by repositioning the ultrasonic probe to the dovetail slot, this area could be fully inspected. However, it is uncertain whether, even if the probe had been repositioned, a detectable crack existed in the incident spool at the time of the 1994 inspections.

The Safety Board concludes that because the currently prescribed in-service inspection techniques do not provide 100 percent inspection coverage of the HPC stage 3-9 spool, these inspections do not ensure the detection of all cracks. Although improved inspection coverage might not have affected the outcome of this incident, the Safety Board is nonetheless concerned that the inspection techniques currently in use permit blind spots in the area of the dovetail blade slots, which are high-stress areas of the spool. Therefore, the Safety Board believes that the FAA should require GEAE to develop and implement improved inspection techniques that will provide 100 percent inspection coverage of high-stress areas of the CF6-50 and -80 series HPC stage 3-9 spool and that will provide the maximum coverage possible of other areas. The Safety Board is also concerned that the incomplete inspection coverage of multistage compressor spools may not be limited only to GEAE CF6-50 and -80 series HPC stage 3-9 spools, but may exist for other multistage compressor spools. Therefore, the Safety Board believes that the FAA should review the prescribed nondestructive inspection techniques for all turbine engine multistage titanium compressor spools to ensure 100 percent inspection coverage of high-stress areas and maximum coverage possible for all other areas and, if necessary, require engine manufacturers to develop and implement improved inspection techniques.

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[9]During FPI, a dye is applied to the surface of the part. The dye penetrates cracks and leaves a surface indication detectable with fluorescent light.

[10]Ultrasonic inspection is a nondestructive method in which beams of high-frequency sound waves are introduced into materials to detect subsurface flaws in the material.

[11]GEAE, Air Accident Investigation Branch of the United Kingdom, and Safety Board personnel reviewed the strip charts from the ultrasonic inspection and confirmed that there were no indications requiring any action. (A strip chart is a continuous length of graph paper that is used to record data in relation to time or distance.)

[12]Eddy current inspections measure fluctuations in an alternating magnetic field around a part generated by a transducer carrying an alternating current. The inspection is used to locate surface and near-surface defects. Eddy current inspections of the HPC stage 3-9 spool were not performed in 1994, when the incident engine and spool were last overhauled.

Possible Role of Melt Deviations in Creating Abnormal Microstructure

The investigation has not formally determined the cause of the abnormal microstructure in the incident spool. However, investigators are examining the possibility that it was related to deviations in the melt process that allowed the introduction of oxygen into the melt. The manufacturing records of the ruptured HPC stage 3-9 spool from flight CP30 indicate that the forward section of the spool (stages 3 through 5) was produced by RMI from Heat[13] No. 981897. RMI's manufacturing records for that heat indicate that the titanium electrode[14] shifted position within the crucible[15] during the second melt. The manufacturing records also indicate that about the same time as the electrode's shift in position, the pressure inside the crucible increased from the normal vacuum of about 100 microns of atmospheric pressure to 900 microns of atmospheric pressure.[16] This increase occurred over the space of 1 minute. Approximately 30 minutes later, the pressure had returned to the normal vacuum of about 100 microns of atmospheric pressure. According to RMI, it is likely that the increase in pressure resulted from the electrode's shift in position, which could have allowed the cooling water from the jacket that surrounds the crucible to leak into the melt. Although the extent of the pressure change (known as a "vacuum excursion") was within RMI and GEAE specifications, which permitted pressure deviations of up to 1,000 microns during the second melt, RMI notified GEAE of the vacuum excursion.[17] GEAE accepted the melt. Subsequently, in October 1991, RMI reduced the specifications for permissible vacuum excursions during secondary and final melts to 750 microns.

A review of GEAE manufacturing records showed that 21 HPC stage 3-9 spools, in addition to the flight CP30 spool, were manufactured from RMI Heat No. 981897.[18] On October 31, 1997, the FAA issued Airworthiness Directive (AD) 97-22-14, which required the removal from service of all 21 spools within 30 days. The FAA and GEAE have advised the Safety Board that all of the other HPC stage 3-9 spools that had been manufactured from RMI Heat No. 981897 have been removed from service. According to GEAE, one of those spools has

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[13]A heat, or ingot, is a mass of metal melted into a convenient shape for handling that is later finished by rolling, forging, or other means.

[14]Titanium electrodes for the first (primary) melt consist of cold-pressed compacts containing a mixture of titanium sponge and elemental alloying materials that are welded together into an approximately 15-foot long, 18-inch diameter cylinder. The electrode in the second (intermediate) melt is produced by welding together two or three primary melt ingots end to end. The electrode in the third melt is the melted together mass from the second melt.

[15]The crucible is a water-cooled copper vessel in which the titanium electrode is melted.

[16]An absolute vacuum is zero microns. A standard day pressure of 29.92 inches of mercury is equivalent to 9,875,118 microns.

[17]According to RMI, it notified GEAE of the vacuum excursion because it was close to the maximum excursion allowable (within 100 microns) and its time span was unusually long (approximately 30 minutes).

[18]Of these, only one spool was installed in a U.S.-registered airplane, a Continental Airlines DC-10, N87071. This spool had accumulated 1,075 CSN, far less than the 4,744 cycles that had been accumulated on the spool from flight CP30.

received an ultrasonic, eddy current, and blue-etch anodize (BEA) inspection,[19] and there were no indications of defects or cracks.[20]

According to GEAE, there have been 10 uncontained HPC stage 3-9 spool failures in CF6-50 and -80 series engines.[21] GEAE further indicated that two of these failures, occurring in 1974 and 1979, were caused by fatigue fractures originating from oxygen-rich inclusions in the spools. These spools, which were produced from 16-inch diameter billets melted by RMI, had reportedly accumulated 483 and 2,854 CSN, respectively, at the time of the failures. In a December 5, 1997, letter to the TSB, RMI stated that the furnace records for the two heats from which these spools had been produced showed that minor vacuum excursions had occurred during the initial melt but that those excursions were typical for the production process that was in use and well within RMI and GEAE specification limits. Records also show that one of the heats had an excursion of 600 microns in the second melt (which was within the then-current limits and is within the revised limits for secondary melts).

The Safety Board is concerned that additional HPC stage 3-9 spools or other critical components manufactured from ingots that contain melt variations that can result in abnormal microstructure may be currently in service. Therefore, the Safety Board believes that the FAA should review GEAE's Ti-6242 titanium alloy suppliers' melting records and identify any vacuum excursions or other process deviations that exceed current specifications or that may otherwise cause an inclusion or abnormal microstructure. The Safety Board also believes that based on the results of this review, the FAA should issue an AD to require removal from service and/or inspections of the components manufactured from these melts.

Rapid Propagation of the Crack and the Possible Role of Dwell Time Fatigue

As mentioned above, the fracture morphology of the incident spool was atypical in that most of the fracture region contained brittle cleavage-like, faceted features, rather than classical fatigue striations. Further, the areas of classical fatigue striations included evidence of only 800 flight cycles, indicating a very rapid crack propagation. This fracture morphology is similar to that

[19]In 1991, GEAE began performing BEA inspections on the surface of newly manufactured spools as a further measure to prevent spools with microstructural anomalies from being put into service. However, within areas of generally abnormal microstructure, the arrangement of alpha and beta grains may be such that a given cross-section of the material may not indicate an abnormality that would be apparent from a different view. Therefore, although it is possible that a BEA inspection could detect an area of abnormal microstructure such as that in the incident spool, it is also possible that the microstructure at the surface might not exhibit an abnormal appearance and thus would not be detected by a BEA inspection.

[20]The AD did not require that the spools be subjected to testing after being removed from service.

[21]The Safety Board has previously expressed concern about the continued airworthiness of GEAE CF6-50 and -80 series engine HPC stage 3-9 spools. In 1995, the Safety Board assisted the Egyptian Civil Aviation Authority with the investigation of an uncontained failure of a GEAE CF6-50 HPC stage 3-9 spool that occurred on an Egypt Air Airbus A300B4 during takeoff at Cairo, Egypt, on April 10, 1995. The failure of that spool was caused by a fatigue crack that initiated from a nitrogen-stabilized hard-alpha inclusion in the web portion of the stage 6 disk.

exhibited in several earlier fractures of CF6-50 and -80 series 3-9 spools[22] that were attributed to a cracking phenomenon that became known as dwell time fatigue (DTF). (The Safety Board first became aware of DTF in 1995 during the investigation of the uncontained failure of the CF6-50 stage 3-9 spool that occurred on the Egypt Air Airbus A300.)

DTF refers to a fracture mechanism in which progressive crack growth occurs during cyclic loading (rise and fall of stress) and also over time during sustained peak-stress loading (during the dwell time at the peak stress level), both at low temperature. The fracture morphology is characterized by subsurface initiation and brittle, faceted-cleavage fracture features. According to GEAE, the DTF phenomenon is related to increased plastic strain and slip along crystallographically aligned alpha colonies[23] in the material microstructure. According to metallurgical research literature, the faceted fracture features that occur during DTF in alpha-beta titanium alloys are associated with large primary alpha colonies possessing a similar crystallographic orientation.[24] Other literature indicates that DTF develops at high stresses (approaching the yield stress of the material) and is associated with hydrogen embrittlement developed during time-dependent plastic deformation at the dwell stress.[25]

GEAE conducted a test program[26] that indicated that a significant reduction in a material's fatigue life occurs when it is subject to DTF as compared to conventional fatigue cycling. However, GEAE has been unable to determine the time it takes from manufacture until a crack initiates or the propagation rate of a crack once it initiates in DTF. Absent a predictable crack initiation time and propagation rate (which can be used to establish required inspection intervals designed to detect cracks before they propagate to failure), the prior failure history of the component provides the only data on which to base inspection intervals.

On August 25, 1995, as a result of a review of the spool failures associated with the DTF phenomenon, the Safety Board issued Safety Recommendation A-95-85 urging the FAA to revise AD 95-03-01 (applicable to GEAE CF6-50, -80A, and -80C2 model engines) to require repeated inspection of all HPC stage 3-9 spools that had been solution heat treated after welding.[27] The

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[22]Of the 10 aforementioned uncontained HPC stage 3-9 spool failures, GEAE attributed 4 of the failures to the DTF fracture mechanism. [(a) the 1985 failure in Dakar, Senegal, of a CF6-50, stage 9 disk with 4,075 CSN, which was part of a one-piece spool; (b) the 1991 failure in Seoul, Korea, of a CF6-50, stage 9 disk with 10,564 CSN, which was part of a one-piece spool; (c) the 1993 failure in Los Angeles, California, of a CF6-80C2 stage 6 disk with 4,403 CSN, which was part of a one-piece spool; and (d) the 1995 failure in Bangkok, Thailand, of a CF6-50 stage 8 disk with 8,438 CSN, which was part of a one-piece spool.]

[23]Crystallographically aligned alpha colonies are areas of the microstructure in which a group of alpha grains in proximity to one another have their crystallographic planes similarly oriented.

[24]Woodfield, A.P. et. al. 1995. "Effect of Microstructure on Dwell Fatigue Behavior of Ti-6242." *Titanium '95: Science and Technology.* p. 1116-1123.

[25]Hack, J. E.; Leverant, G. R. 1982. "The Influence of Microstructure on the Susceptibility of Titanium Alloys to Internal Hydrogen Embrittlement." *Metallurgical Transactions*, Volume 13A. p. 1729–1738.

[26] The results of this test program are documented in "Effect of Microstructure on Dwell Fatigue Behavior of Ti-6242," published in *Titanium '95: Science and Technology.* (See complete citation in footnote 24, above).

[27]Until 1995, all two-piece spools received a postweld solution heat treatment followed by a slow cool down. In 1995, according to GEAE, it replaced the solution heat treatment process with a postweld stress-relief process to

Safety Board urged that the maximum interval between inspections should be appropriately less than the 4,000 cycles specified in that AD.[28]

The FAA responded that it agreed with the safety recommendation to require inspections of most GEAE CF6-50, -80A, and -80C2 HPC stage 3-9 spools but did not agree that there should be a maximum interval between all inspections. On November 13, 1995, the FAA issued AD 95-23-03, superseding AD 95-03-01, which reduced the repetitive inspection interval requirements for one-piece HPC stage 3-9 spools made from 16-inch diameter billets used in GEAE CF6-50, -80A and -80C2 engines from a maximum of 4,000 cycles to a maximum of 3,500 cycles. A 3,500-cycle inspection interval was also established for spools made from 13-inch diameter billets that are used on GEAE CF6-80C2 engines. However, the FAA did not make any requirements for mandatory repetitive inspections for one-piece HPC spools made from 13-inch diameter billets installed in CF6-80A engines or on any spools made from two-piece forgings.

In its April 16, 1996, response to the FAA, the Safety Board expressed its concern that further failures of stage 3-9 spools could occur at the 3,500-cycle inspection interval and stated that it believes the 3,500-cycle inspection interval was based primarily on economic considerations, not on fracture propagation or low-cycle failure events. The Safety Board response further stated that the earliest DTF separation of a compressor spool had occurred after 4,075 CSN in a spool made from a 16-inch diameter billet. The Safety Board also investigated the separation of an HPC spool made from a 13-inch diameter billet that occurred in a CF6-80C2 engine after 4,403 CSN. The pieces of the separated spool containing the fracture origin area were not recovered, so the exact fracture mechanism was not determined. However, the investigation concluded that the aligned alpha colonies in the microstructure of the spool made it susceptible to DTF. These spool separations indicate that complete failure resulting from DTF can occur after a relatively low number of cycles.

In a December 3, 1996, letter, the Safety Board indicated that AD 95-23-03 did not satisfy the intent of Safety Recommendation A-95-85, and the recommendation was classified "Closed—Unacceptable Action."

The Safety Board notes that in addition to having a fracture morphology similar to that of the spools that failed from DTF, the fracture of the stage 3 disk on flight CP30 initiated at a subsurface location in an area of high stress, and the material microstructure contained an aberrant alpha structure. Although the fracture initiation area of the flight CP30 spool did not exhibit crystallographically aligned alpha grains, such as has been associated with previous DTF fractures, it did contain an area of predominately alpha phase. In contrast, the fracture mechanism on the spool of the Egypt Air Airbus A-300 that failed in 1995, which was also made from Ti-6242,

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eliminate what GEAE had determined to be a propensity for grain growth and crystallographically aligned alpha colonies that occurred during the slow cool down from high temperature.

[28]AD 95-03-01, issued on February 16, 1995, required repetitive (at intervals not to exceed 4,000 cycles) ultrasonic and eddy current inspections of spools made from 16-inch diameter billets. (AD 91-20-01, issued October 25, 1991, had earlier required one-time [within 3,500 cycles] ultrasonic and eddy current inspections of spools made from 16-inch diameter billets.)

showed classical fatigue striations that correlated by striation count to the total engine cycles for the spool (indicating much slower propagation rates than those produced by DTF). Further, the fracture features on the Egypt Air spool did not contain cleavage-like, faceted fractures like those associated with DTF, nor did the microstructure contain any aberrant alpha phase. This shows that not all fatigue failures of the Ti-6242 alloy exhibit this unusual fracture morphology and those that do have aberrant alpha phase in the microstructure.

This suggests that although stage 3-9 spools made from Ti-6242 that have a normal, homogeneous alpha/beta microstructure can operate in service free of any cracking, if the spool has an abnormal alignment or distribution of alpha grains in a high-stress area, it can fracture unpredictably and rapidly. Although the Safety Board recognizes that failures associated with DTF and the failure of the 3-9 spool from flight CP30 might also have been affected by other as-yet-unknown factors, the Safety Board concludes that CF6-50 and -80 series HPC stage 3-9 spools may be uniquely susceptible to unpredictable crack-initiation times and rapid-crack growth rates. Therefore, the Safety Board believes that the FAA should conduct a critical design review of CF6-50 and -80 series HPC stage 3-9 spools to assess the overall safety and soundness of the part. The review should, at a minimum, evaluate the following: the adequacy of current and past manufacturing processes, including the ability of current and previous melt specifications and postweld procedures to protect against the creation of microstructural abnormalities; the propriety of using Ti-6242 titanium alloy, including the possible susceptibility of this alloy to the development of aberrant or undesirable crystallographic arrangements of alpha phase and a resulting vulnerability to rapid cracking; and the adequacy of the stress margins for the spool in the presence of an aberrant or undesirable microstructure.

Further, the Board remains concerned that not all CF6-50 and -80 series HPC stage 3-9 spools are required to be subjected to repeated inspections at intervals appropriately less than 4,000 cycles. Further, because it is not yet known (because the change is too recent) whether the cessation in 1995 of the postweld solution heat treatment has eliminated the susceptibility of those parts to DTF, it is possible that even those spools that were not subjected to this process are vulnerable. Therefore, the Safety Board believes that the FAA should revise AD 95-23-03, applicable to GEAE CF6-50, -80A, and -80C2 model engines, to include the -80E model engines, and to require repeated inspections of all HPC rotor stage 3-9 spools at maximum intervals appropriately less than 4,000 cycles.

Therefore, the National Transportation Safety Board recommends that the Federal Aviation Administration:

> Require General Electric Aircraft Engines to develop and implement improved inspection techniques that will provide 100 percent inspection coverage of high-stress areas of the CF6-50 and -80 series high-pressure compressor stage 3-9 spool and that will provide the maximum coverage possible of other areas. (A-98-27)
>
> Review the prescribed nondestructive inspection techniques for all turbine engine multistage titanium compressor spools to ensure 100 percent inspection coverage of high-stress areas and maximum coverage possible for all other areas and, if

necessary, require engine manufacturers to develop and implement improved inspection techniques. (A-98-28)

Review General Electric Aircraft Engines' Ti-6242 titanium alloy suppliers' melting records and identify any vacuum excursions or other process deviations that exceed current specifications or that may otherwise cause an inclusion or abnormal microstructure. Based on the results of this review, issue an airworthiness directive to require removal from service and/or inspections of the components manufactured from these melts. (A-98-29)

Conduct a critical design review of CF6-50 and -80 series high-pressure compressor stage 3-9 spools to assess the overall safety and soundness of the part. The review should, at a minimum, evaluate the following:

- the adequacy of current and past manufacturing processes, including the ability of current and previous melt specifications and postweld procedures to protect against the creation of microstructural abnormalities; (A-98-30)

- the propriety of using Ti-6242 titanium alloy, including the possible susceptibility of this alloy to the development of aberrant or undesirable crystallographic arrangements of alpha phase and a resulting vulnerability to rapid cracking; (A-98-31) and

- the adequacy of the stress margins for the spool in the presence of an aberrant or undesirable microstructure. (A-98-32)

Revise Airworthiness Directive 95-23-03, applicable to General Electric Aircraft Engines CF6-50, -80A, and -80C2 model engines, to include the -80E model engines, and to require repeated inspections of all high-pressure compressor rotor stage 3-9 spools at maximum intervals appropriately less than 4,000 cycles. (A-98-33)

Chairman HALL, Vice Chairman FRANCIS, and Members HAMMERSCHMIDT, GOGLIA, and BLACK concurred in these recommendations.

Jim Hall

By: Jim Hall
Chairman

National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

Date: March 17, 1998

In reply to refer to: A-98-40

Honorable Jane F. Garvey
Administrator
Federal Aviation Administration
Washington, D.C. 20591

On June 17, 1997, just after takeoff from Las Vegas, Nevada, a Reno Air McDonnell Douglas MD-83 airplane, N875RA, operating as flight 516, experienced an uncontained failure of the No. 1 (left) engine, a Pratt & Whitney (P&W) JT8D-219, serial number (SN) 708177. The airplane returned to Las Vegas and landed without further incident. The airplane was operating on an instrument flight rules flight plan under the provisions of Title 14 Code of Federal Regulations Part 121 as a regularly scheduled passenger flight from Las Vegas to Colorado Springs, Colorado. The investigation of this incident is continuing; however, information gathered thus far raises safety concerns that the National Transportation Safety Board believes require Federal Aviation Administration (FAA) action.

During the aircraft's ascent after takeoff, high-pressure turbine (HPT) parts were liberated from the engine. Inspection of the airplane revealed two exit holes in the engine nacelle and one hole in the fuselage in a nonpressurized compartment of the airplane. Postincident examination of the engine revealed four exit holes in the combustion chamber fan ducts just forward of the HPT rotational plane, yet the HPT case (front turbine case) was not penetrated. Two sections of the HPT case rear flange were bent outward and forward, and were disengaged from the low-pressure turbine (LPT) case (rear turbine case) front flange, creating two large openings. The HPT shaft had sheared at the No. 4 ½-bearing scavenge oil holes; all the HPT blades fractured transversely across the blade airfoil; and all the 2nd-stage turbine vanes were missing.

The engine was equipped with an HPT containment shield (see figure 1) as required by Airworthiness Directive (AD) 93-23-10.[1] The AD was issued on January 18, 1994, and is

[1] The containment shield is intended to prevent engine HPT parts from being liberated and causing secondary damage to the airplane or injuring passengers. The shield is positioned radially outward from the rotational plane of the HPT blades. The width of the containment shield is approximately 4 inches, and its support attaches to the HPT case rear flange. The support, although it provides some containment capability, is primarily to buttress and properly position the containment shield.

applicable to all JT8D-209, -217, -217A, -217C, and -219 turbofan engines. The containment shield is a clam shell design consisting of two half-shields joined by clevis plates and supported by a cantilevered shield support attached to the HPT rear flange. Considerable impact damage (engine debris) was observed on the inner diameter (ID) of the containment shield; however, the shield remained intact. The impact of turbine material on the lower shield shifted it outward and aft from its normal installed position, buckling its support. First-stage turbine blades and 2nd-stage turbine vanes had exited the engine through the openings between the HPT and LPT case flanges and deflected off the containment shield ID while exiting the engine and before striking the airframe.

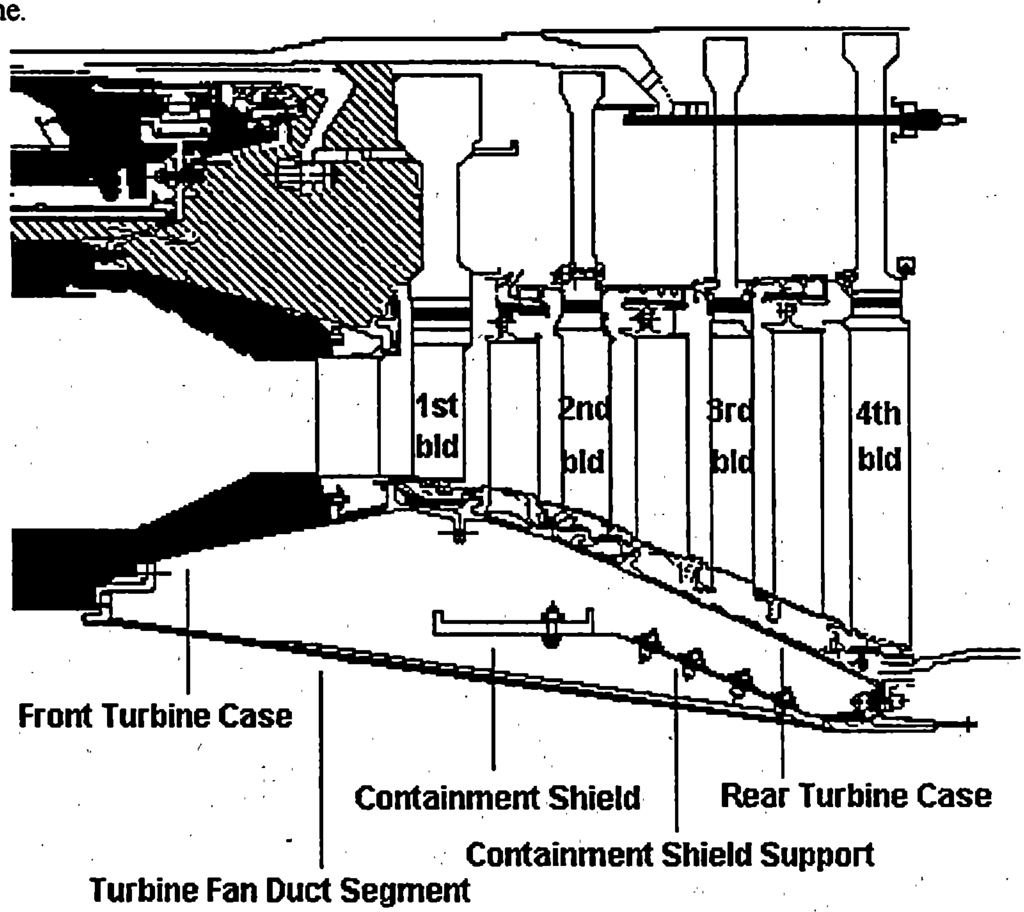

Figure 1 Containment Shield Configuration

Another incident involving a P&W JT8D-219 uncontained turbine failure that resulted from a sheared HPT shaft occurred on July 13, 1996, on a Centennial Airlines[2] McDonnell Douglas MD-80 airplane, en route from Dusseldorf, Germany, to the Canary Islands. Like the Reno Air incident, the failed engine was equipped with an HPT containment shield, which was not

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[2] Centennial Airlines is a Spanish-registered supplemental air carrier based in Palma de Mallorca, Spain.

penetrated; however, exiting turbine parts impacted the shield ID, buckled its support, and shifted the shield from its normal position. The buckled support allowed the exiting turbine parts to deflect off the shield and penetrate the engine nacelle.

On November 7, 1991, after the JT8D-200 series engine had experienced six HPT shaft fractures, three resulting in the liberation of turbine parts, P&W issued Alert Service Bulletin (ASB) 6053 to incorporate a containment shield for JT8D-209, -217, 217A, -217C, and -219 engines.[3] Subsequently, P&W issued Service Bulletin (SB) 6122 on May 20, 1993, to address premature wear of the support slip joint caused by buffeting of the shield. The basic design stayed the same; however, new hardware with hardfacing[4] on the mating surfaces was incorporated. AD 93-23-10 required JT8D-200 series engines to be outfitted with a containment shield as instructed by P&W ASB 6053, Revision 7, dated May 24, 1993. The FAA's Engine Certification Manager, ANE-140, issued a letter on June 28, 1994, approving SB 6122 as an equivalent means of compliance to AD 93-23-10.

The Reno Air and Centennial Airlines incidents have shown that the JT8D-200 series engine HPT containment shield design is inadequate to prevent all turbine parts from being liberated because the support is insufficient to sustain the shield in the proper location when impacted by some exiting turbine material. In addition, the incidents have shown that the containment shield is not wide enough nor the sidewalls deep enough to ensure that exiting material will be contained under a variety of exit paths. The Safety Board is concerned that the current containment shield cannot prevent HPT part liberation and therefore believes that the FAA should evaluate the current P&W JT8D-200 series engine HPT containment shield required by AD 93-23-10 and, if shown by evaluation, require that it be replaced with an HPT containment shield that would provide a larger coverage area and more impact resistance and durability.

Therefore, as a result of the ongoing investigation of this incident, the National Transportation Safety Board recommends that the Federal Aviation Administration:

> Evaluate the current Pratt & Whitney JT8D-200 series engine high-pressure turbine (HPT) containment shield required by Airworthiness Directive 93-23-10 and, if shown by evaluation, require that it be replaced with an HPT containment shield that would provide a larger coverage area and more impact resistance and durability. (A-98-40)

Chairman HALL, Vice Chairman FRANCIS, and Members HAMMERSCHMIDT, GOGLIA, and BLACK concurred in this recommendation.

By: Jim Hall
Chairman

[3] At the time ASB 6053 was issued there had been six documented HPT fractures resulting from No. 4 and 5 bearing compartment oil fires, three of which have resulted in uncontained events.

[4] Hardface is a seal facing of high hardness that is applied to a softer material, such as by flame spraying, plasma spraying, electroplating, nitriding, carburizing, or welding for better wear resistance.